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SHIPTRAP: A capture and storage facility on its way towards an RIB-facility

G. Marx*, J. Dilling*, H.-J. Kluge*, M. Mukherjee*, W. Quint*,
S. Rahaman*, D. Rodriguez*, G. Sikler*, M. Tarisien*, C. Weber* and the
SHIPTRAP Collaboration[†]

*GSI Darmstadt, Postfach 110552, D-64220 Darmstadt, Germany

[†]

Abstract. First off-line tests at the ion trap facility SHIPTRAP took place. The facility is being set up to deliver very clean and cooled beams of singly-charged recoil ions produced at the SHIP velocity filter at GSI, Darmstadt. SHIPTRAP consists of a gas cell for stopping and thermalizing high-energy recoil ions from SHIP, an rf ion guide for extraction of the ions from the gas cell, a linear rf trap for accumulation and bunching of the ions, and a Penning trap for isobaric purification. The physics programme of the SHIPTRAP facility comprises mass spectrometry, nuclear spectroscopy, laser spectroscopy and chemistry of transeinsteinium elements. The progress in testing the sub-systems separately and in combinations is reported.

INTRODUCTION

The interest in coupling ion traps to sources of radionuclides arises from the extremely small phase space in which ions reside in a trap, from the possible long storage time and from the extremely high purity that can be obtained. These are pre-requisites for high-accuracy experiments. The purification is very important since contaminants always plagued the investigation of exotic radioactive species. This separation not only allows for very sensitive and accurate experiments to be performed within the ion trap itself but also allows the collected radionuclides to be extracted from the trap and studied in a well-defined low-emittance ion beam. Together, these possibilities open a wide range of physics applications. SHIPTRAP will enable very sensitive and accurate experiments, performed within the ion trap itself or with an extracted beam. The half-lives of the most neutron-rich nuclides of the elements up to hassium ($Z = 108$) are longer than one second, which is also predicted by theory for a large number of ions in this region of the chart of nuclei. This is long enough to prepare the ions and to perform precision experiments. The ISOLTRAP experiment at ISOLDE/CERN [1], consisting of a rf trap for accumulation of the 60-keV ISOLDE ion beam, a first Penning trap for isobar separation and a second one for high-accuracy mass measurements of short-lived isotopes, has demonstrated the potential of the ion trap concept at ISOL (Isotope Separation On-Line) facilities. The present state of ion trap technology now makes it possible to couple a trap system to ion beams of higher energy (about 0.5 MeV/u) such as delivered by the velocity filter SHIP (separator for heavy-ion reaction products) at GSI. A similar project has been started at a recoil separator at Argonne (USA) while at INS (Tokyo)

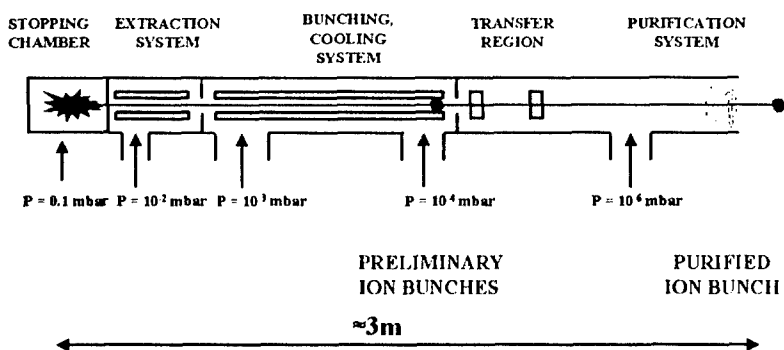


FIGURE 1. The overall SHIPTRAP configuration

a radiofrequency trap coupled to GARIS [2] has already been tested. The advantage of such facilities is that they enable the rich variety of physics experiments currently performed at ISOL facilities to be extended to isotopes for which target/ion source systems do not exist at ISOL facilities. The particular advantage that SHIPTRAP will have is the ability to extend these experiments to transuranic nuclides. Thus, SHIPTRAP will enable the application of refined ISOL techniques for the first time to nuclides with nuclear charge $Z > 92$, extending even to the superheavy elements of which many have a sufficiently long half-life for trap technology.

THE SHIPTRAP FACILITY

SHIP is a kinematic separator for reaction recoils from thin targets irradiated by beams from the heavy-ion linear accelerator UNILAC at GSI [3]. It is optimized for the separation of heavy elements produced by fusion of projectiles from $A = 40$ to 80 with heavy target nuclei such as lead or bismuth. The primary beam has an energy close to 5 MeV/u and time-averaged intensities of typically $2 \cdot 10^{12}$ - $5 \cdot 10^{12}$ ions/s.

The SHIPTRAP facility is setup at the exit of SHIP. It stops and thermalizes the produced recoil ions in a noble gas from which they are then extracted and collected in a trap. The system is outlined in Fig. 1. It consists of a stopping chamber containing the noble gas, an extraction system to bring the stopped ions into a vacuum region, a radiofrequency trapping system to collect the ions in this vacuum region and to cool them

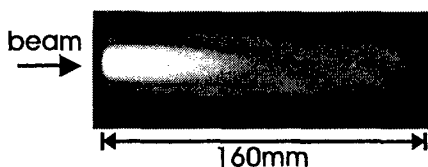


FIGURE 2. Stopping of Au^+ ions with an energy of 0.3 MeV in argon at 80 mbar. The light emitted in this process is recorded by a CCD-camera.

into well-defined bunches which are then extracted and injected into a Penning trap for isobaric purification. The Penning trap accumulates the ion bunches, filters out possible contaminants and further cools the collection to room temperature. This collection is then extracted on the demand of downstream experiments.

The noble gas in the stopping chamber, at pressures around one-tenth of an atmosphere, will thermalize recoil ions preferentially in the singly ionized state. An electric field, together with the gas flow, then guides the ions out of the chamber into the extraction system where they are separated from the gas. This system is a short quadrupole rod structure that confines the ions to its axis by an rf field while the noble gas is pumped away. An axial dc electric field applied to the segmented rods guides the ions along the axis towards the bunching system. The recent development for the SHIPTRAP stopping chamber and the extraction RFQ is described elsewhere [4]. In the ion bunching system, a 1m quadrupole rod structure immersed in a low-pressure buffer gas, the ions are trapped by a proper choice of longitudinal dc and transverse rf fields and cooled in collisions with the buffer gas. The RFQ-buncher has been set up and is currently being tested. The purification system into which these preliminary bunches are collected is based on a Penning trap similar to the one used for this purpose at the ISOLTRAP facility at ISOLDE. In such a system the contaminating isotopes are very effectively suppressed due to the high mass resolving power of the cooling process. Depending on the trapping time it can reach $M/\delta M(\text{FWHM}) = 10^5$.

The ion bunches delivered by this Penning trap system will have extremely low emittances, thermal energy spreads and pulse durations of typically less than a microsecond, although bunches of longer duration could be extracted if desired. With current ISOL beam technology these bunches could be delivered at any energy desired up to about 60 keV. In some cases it may be advantageous to use specifically those ions from SHIP that become neutral atoms in the stopping gas. These can then be re-ionized by a laser beam (resonance ionization spectroscopy, RIS) for delivery to the vacuum system. Such a scheme provides element selectivity, and for heavy elements isotopic selectivity as well, in the stopping chamber itself.

THE STOPPING CHAMBER AND THE EXTRACTION SYSTEM

A prototype gas cell was designed for tests at the Tandem Accelerator in Garching and at SHIP. At Garching, stopping of 0.3 MeV/u gold ions in a 80 mbar argon atmosphere was measured by detecting the light which is emitted during the electronic stopping

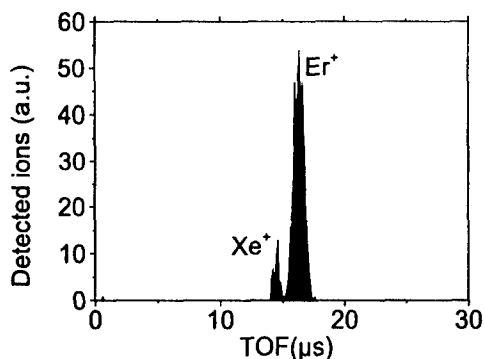


FIGURE 3. Test of stopping chamber: Erbium ($^{166}\text{Er}^+$) and xenon ($^{132}\text{Xe}^+$) ions are laser ionized in the stopping chamber, accumulated in the RFQ buncher, extracted and detected by a multi-channel plate.

process with a CCD-camera (Fig.2). In the SHIPTRAP setup the beam of exotic nuclei produced and pre-separated at SHIP will enter the He-filled stopping chamber through a thin window [4]. In addition to the gas flow, static and RF fields guide the predominantly singly charged ions to the exit nozzle. The stopping gas is pumped off outside the extraction hole and the diverging beam is re-focused by the oscillating field of the following extraction RFQ. The prototype has been tested with ions internally produced by laser desorption (laser pulse width: 6 ns, repetition rate: 25 Hz) from an erbium filament inside the stopping chamber. The helium gas pressure in the stopping chamber was set to 20 mbar. The ions are guided into and accumulated in the RFQ buncher for 300 ms. The trapped and extracted ions are identified by time of flight (see Fig.3). No statement is possible for the efficiency of the transfer from the stopping chamber to the extraction system.

THE RFQ BUNCHER

The classical Quadrupole Mass Analyzer (QMA) is operated by applying on its rods a dc bias voltage U and a radio-frequency of amplitude V and frequency ω_{rf} . An ion with mass m and charge e , which enters the QMA performs an oscillation which is described by solution of the Mathieu equations. In this equation one defines a pair of dimensionless parameters a ($-\frac{4eU}{m\omega_{rf}^2 r_0^2}$), proportional to the dc bias voltage U and q ($\frac{2eV}{m\omega_{rf}^2 r_0^2}$), proportional to the rf amplitude V . This pair of parameters characterizes the working point in a a, q -stability diagram. The motion of the ion is stable if the amplitude of the oscillation remains finite, and unstable if its amplitude rises exponentially. In our case the QMA was tested in rf-only mode, i.e. without a dc voltage U . Then the operating region lies on the q axis. For a certain rf voltage applied to the rods, all ions pass the filter for which q is less than the stability limit 0.908. The rods of the SHIPTRAP RFQ have

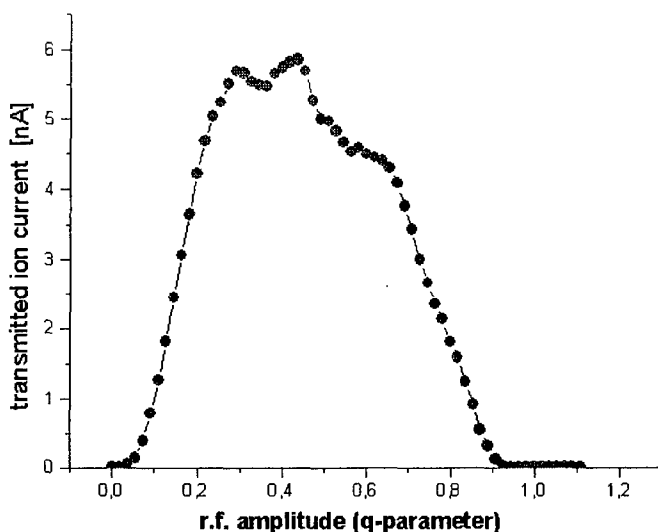


FIGURE 4. Transmission plot in rf-only mode for Ar^+ ions.

a diameter of 9 mm. The distance between two opposite rods is 7.86mm. In first tests in the rf-only mode with a calibrated ion source a transmission of about 93(5)% was achieved. Fig.4 shows a transmission plot for Ar^+ ions. The driving field frequency was set to $\nu_{rf} = 600\text{kHz}$. In simulations it was shown that the left edge of the transmission curve is affected by beam divergence, whereas the right edge is rather unaffected [6]. A lower transmission for low q values as beam divergence grows can be explained by the fact that ion entry angle grows; hence the probability of hitting the rods increases. The right edge is affected by beam width effects, becoming less abrupt as beam width grows. In simulations it was shown that this effect is more pronounced when the ion beam is not centered or annular. As a conclusion our transmission curves are indicating an off-axis ion source with low emittance.

The essential task of the RFQ buncher at SHIPTRAP is to accept the ions from the stopping chamber, to cool and to collect them. Therefore the RFQ buncher will be operated under buffer gas and it is necessary to investigate the influence of gas on the ion motion. The average effect of ion collisions with buffer gas molecules can be approximated by a frictional drag force. This is described by the Mathieu equation for the ion motion in free space but with an added velocity dependent term. Figure 5 shows three measured transmission curves at different pressures. One can see a tendency that the right edge of the stability diagram is shifted to higher q -values. Due to the damping of the ion motion one can apply higher quadrupole field strength until the ion motion becomes unstable. The information how much the stability region is increased under buffer gas operation is important since one tries to use the (limited) mass resolution of

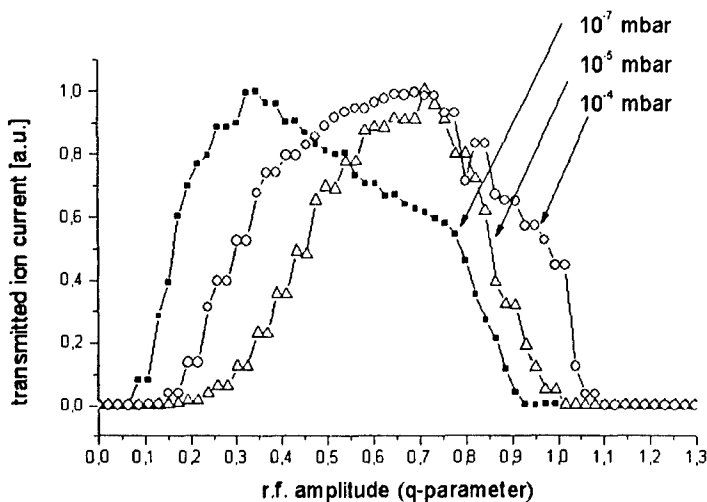


FIGURE 5. influence of buffer gas on the transmission curve

the RFQ in rf-only mode to suppress contamination of lighter ion species.

The qualitative overall effect of space charge on an ion beam in an RFQ rod structure, neglecting the size of an ion beam due to thermal motion of the ions, will push out the ions until those at the periphery of the beam experience an effective radial electric force from the confining field that balances the radial expansion force of the space charge. Assuming a uniform charge distribution along the beam axis, the space charge electric field at the edge of a beam of radius r is balanced by the effective trapping electric field. This results in a charge density $\rho_z = \frac{\pi\epsilon_0 m}{4} q^2 \omega_{rf} r^2$. For a typical set of operating conditions ($q=0.45$; $\omega_{rf}/2\pi=1\text{MHz}$; $r=2\text{mm}$; $m=100\text{amu}$) the linear charge density will be about 0.2nC/m . For the SHIPTRAP RFQ buncher of 1m length assuming a drift field to give the ions an axial velocity of 1000 m/s , the ion density along the device result in a maximum beam current of about 200 nA . Our tests have been done well below this space charge limit.

Trapping times of up to 30 s without significant ion loss have been achieved. Accumulation of ions with a dc-injection as well as a pulsed injection was demonstrated. The ions can be extracted in a pulsed mode in bunches with high phase space density and can be delivered to the high vacuum region.

THE PENNING TRAPS

A double trap system is installed within one magnet at SHIPTRAP. Both traps have cylindrical electrodes with an inner diameter of 30 mm . The purpose of the first trap is

to catch the ion bunch from the RFQ buncher and to purify the ion bunch. The second trap is for, e.g., mass measurements. The traps (distance between the centers of traps: 10 cm) are separated by a diaphragm.

Penning trap mass spectrometers at ISOLDE/CERN [1], Stockholm [7], and Argonne [8] use a time-of-flight method developed by Gräff et al. [9] to measure eigenfrequencies of trapped ions. The ions are ejected out of the trap and their time of flight to a detector is recorded. Typically this requires the detection of 100 - 1000 ions. Assuming a production rate in the order of 10^{-3} ions/s, e.g. for Sg ($Z = 106$), this would lead to a beam time of about 1 - 10 days. A non-destructive way to obtain eigenfrequencies of the ion motion is to monitor the image currents induced in the trap electrodes by the oscillating ions (Fig.6). Such a method is employed, e.g. at the University of Washington [10] and at MIT [11]. It allows the non-destructive identification of one single ion, and the required beam time for the mass measurement of a heavy element is much less than one day. In order to determine the detection sensitivity of such a device one has to estimate the image current which is given by

$$I_{ion} = \frac{1}{\sqrt{2}} \frac{r_{ion}}{D} \cdot q \cdot \omega_{ion}. \quad (1)$$

This signal can be detected via a tank circuit of quality factor Q . Taking into account the thermal noise of the circuit, the signal-to-noise ratio (S/N) is given by

$$\frac{S}{N} = \frac{\sqrt{\pi}}{2} \cdot \frac{r_{ion}}{D} \cdot q \cdot \sqrt{\frac{v}{\Delta v}} \sqrt{\frac{Q}{kT \cdot C}}, \quad (2)$$

where r_{ion} is the radius of the ion orbit in the trap, D characterizes the trap size, T is the temperature, and C the stray capacitance of the system. The signal-to-noise ratio can be optimized by a high quality factor Q , a low temperature T , and by minimizing the capacitance C . The setup at SHIPTRAP will consist of a cryogenic system with the trap environment at liquid nitrogen temperature and a superconducting tank circuit at 4 K. With an effective temperature of 30 K and an estimated Q of 1000 the power signal-to-noise ratio will be higher by a factor of 50 as compared to a room temperature setup.

THE SCIENTIFIC CASE FOR SHIPTRAP

Nuclear mass measurements of transuranium isotopes

A high-resolution Penning trap mass spectrometer coupled to the SHIPTRAP facility will allow for direct mass spectrometry of heavy actinide and transactinide isotopes, provided the background of unwanted ions can be sufficiently suppressed. In such measurements nuclear binding energies can be determined with high precision. Investigations of the heaviest elements at SHIP has led to the discovery of a shell-stabilized deformed region centered at $Z = 108$ and $N = 162$. This region of enhanced stability against fission interconnects the transuranium elements and the predicted superheavy shell located at

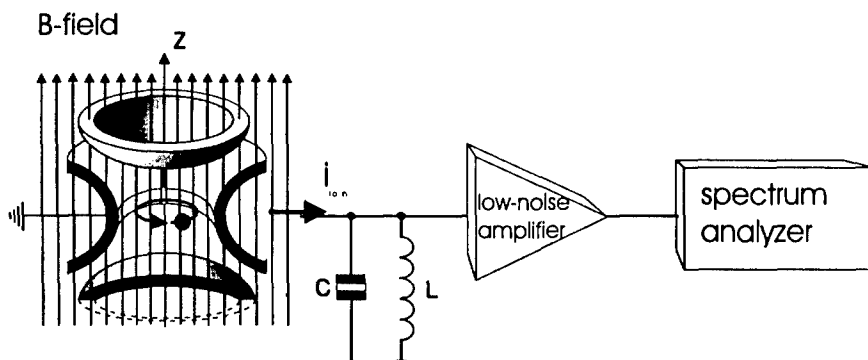


FIGURE 6. Principle of non-destructive FT-ICR technique. The image current of a single singly charged ion is picked up on a split electrode, amplified and analyzed.

$Z = 114$ and $N = 184$ [12]. For the most neutron-rich isotopes of the elements up to hassium ($Z = 108$) half-lives longer than 1 s were observed. These long half-lives open the possibility of high-accuracy mass measurements on heavy elements with ion traps [13].

Precision nuclear spectroscopy

SHIPTRAP will be an excellent facility for precision nuclear spectroscopy of short-lived nuclei. For such studies the bunches of radioactive ions will be delivered to a subsequent Penning trap. In this case, the Penning trap employed is a simple containment device, requiring as high a magnetic field as possible but with minimal requirements on magnetic field uniformity and electric field shape. Such a trap provides a radioactive "source" of a particular nuclear species that is completely free of the absorption and backscattering problems created by the backing material, problems that have plagued all previous high-precision nuclear spectroscopy on nuclear decays. Furthermore, because of the high magnetic field of such a trap, an array of beta, gamma and charged-particle detectors can be configured so that each detector presents a very clean spectrum of the activity it is meant to observe, suffering little background from the others. By including the observations of charged particles, studies can be made on β -delayed proton emission, β -decay and decay by cluster emission.

Nuclear fission studies

A careful study of nuclear fission gives a deeper insight into the influence of shell effects on nuclear dynamics. Fission-fragment mass distributions and total kinetic energies can vary significantly from one nucleus to another. For example, ^{256}Fm shows a double-humped mass distribution, similar to that for the lighter actinides, while ^{258}Fm

exhibits a narrow, symmetric mass distribution and exceptionally high total kinetic energies. This finding has been attributed to the influence of the double shell closure in ^{132}Sn on the fission process [14]. Another transition from asymmetric to symmetric fission has been observed around ^{226}Th . Knowledge of the systematics of the fission properties of nuclei leads to an improved understanding of nuclear-structure effects on nuclear dynamics. The experimental method which is best suited to study the fission properties of spontaneously fissioning nuclei which are only available in small numbers is to measure the energies of the two fission fragments in two opposite detectors.

Chemistry

One of the most fascinating studies of the heaviest actinides and the transactinides concerns the influence of increasingly strong relativistic effects on the valence-electron configuration of the atom and its consequences on chemical behaviour. The aim of such experiments is to compare the chemical properties with homologous elements. For example, the element $Z = 105$ (dubnium) is the chemical homologue to niobium ($Z = 41$) and tantalum ($Z = 73$) in group 5 of the Periodic Table. However, it is well known that relativistic effects gain an increasingly important role for the heaviest elements around $Z = 100$ and consequently the atomic and chemical properties of these elements may not behave as expected from periodicity. The valence electron configurations of these elements can be predicted by multi-configuration Hartree-Fock-Dirac calculations and other methods [15],[16]. At SHIPTRAP, reaction studies of trapped ions with small amounts of a reactive gas in an ion trap would allow kinetic studies by investigating the loss rate of an ionic species from the trap. In addition, this may give access to ion chemical studies of short-lived isotopes of the heaviest elements, which is mandatory for chemical studies in cases where all known isotopes of a given element are short-lived. Traps will also provide access to oxidation states which cannot be investigated with current chemical methods. It is expected that these investigations can be extended to short-lived transactinides with $Z > 106$ and $T_{1/2} < 100$ ms, which are out of reach to gas-chromatographic methods.

Optical spectroscopy of transeinsteinium elements

Laser spectroscopy is a very sensitive method for the investigation of atomic and nuclear properties of rare radioactive species [17]. Many experimental results have been obtained at ISOLDE (CERN) with the method of collinear laser spectroscopy. In special cases only about 100 ions/s are required for high-resolution hyperfine spectroscopy which yields information on the nuclear spin, the nuclear moments and the change of the nuclear charge radius as a function of the neutron number. For production rates of less than 100 ions/s the radiation detected resonance ionization spectroscopy (RADRIS) technique in a buffer gas cell is a powerful method. This method can be employed for the investigation of radioactive nuclides with half-lives as short as 1 ms and which are produced with rates of less than 10 ions/s, as demonstrated in spectroscopic investigations

of ^{240}f , ^{242}f Am fission isomers [18]. The combination of laser spectroscopy with SHIP-TRAP presents a unique possibility of investigating atomic, nuclear and ion chemical properties in the region of superheavy elements.

SUMMARY

The SHIPTRAP facility at GSI Darmstadt is designed to slow down heavy-ion projectiles from the velocity filter SHIP to thermal energies, to accumulate and cool them in an ion trap system and to deliver these ions as isobarically pure ion bunches with low emittance to experiments. After an intense simulating and construction phase all components are presently under test. SHIPTRAP will undergo a test beam time in winter 2001 and will start operation in Summer 2002. The experimental programme which is envisaged by the SHIPTRAP user community promises to give new insights into the nuclear, atomic and chemical properties of elements beyond uranium, the heaviest element available at usual ISOL facilities.

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